

THE INTERNATIONAL SPACE STATION IN SPACE EXPLORATION

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ABSTRACT

The International Space Station (ISS) Program has many lessons to offer for the future of space exploration. Among these lessons of the ISS Program, three stand out as instrumental for the next generation of explorers. These include: 1) resourcefulness and the value of a strong international partnership; 2) flexibility as illustrated by the evolution of the ISS Program and 3) designing with dissimilar redundancy and simplicity of sparing. These lessons graphically demonstrate that the ISS Program can serve as a test bed for future programs. As the ISS Program builds upon the strong foundation of previous space programs, it can provide insight into the prospects for continued growth and cooperation in space exploration. As the capacity for spacefaring increases worldwide and as more nations invest in space exploration and space sector development, the potential for advancement in space exploration is unlimited. By building on its engineering and research achievements and international cooperation, the ISS Program is inspiring tomorrow's explorers today.

Introduction

The International Space Station (ISS) Program is a technological undertaking of global scope. Elements of the ISS are provided and operated by an international partnership, principally the space agencies of Canada, Europe, Japan, Russia and the United States. The construction of the ISS "has been hailed as the most ambitious feat of engineering in human history."¹ While the ISS is not yet complete and some of the

most challenging assembly stages are yet to come, the ISS is already serving as a test bed for exploration, proving the value of flexibility, resourcefulness and designing with redundancy.

The ISS has been continuously crewed for almost six years and is about 50% complete with approximately 186 metric tons of mass on orbit. When assembly is complete, the ISS will be comprised of 453 metric tons of hardware, orbited in about 40 separate launches over more than a decade. To date, there have been over 50 flights to the ISS, including flights for assembly, crew rotation and logistical support.

¹ Discovery Channel: Machines and Engineering. "Building the Biggest: International Space Station".
http://discoverychannelasia.com/machines_engineering/building_the_biggest/iss/index.shtml
(accessed July 30, 2006).

While the Shuttle was grounded, post-Columbia, the ISS partnership maintained the Station using Russian Soyuz and Progress vehicles, learning lessons instrumental for future space exploration. Items that were meant to be returned to the ground for replacement were repaired on orbit, consumables tracking operations were honed and EVAs were performed without a crew member inside the vehicle. In 2006, human presence on board the Station returned to a permanent crew of three and Station assembly resumed.

The ISS partners met at the Heads of Agencies level and agreed to a configuration, assembly sequence and transportation strategy. They reaffirmed their agencies' commitment to meet their mutual obligations, to complete assembly of the ISS by the end of the decade, to implement six person crew capability in 2009 and to use a combination of transportation systems to complete ISS assembly in a timeframe that

meets the needs of the partners and ensures full utilization of the unique capabilities of the ISS throughout its lifetime.

In addition to the U.S. Space Shuttle and Russian Soyuz and Progress vehicles, there are multiple spacecraft, in various stages of development that will be used to maintain and utilize the ISS. These include vehicles resulting from the U.S. Commercial Orbital Transportation Services (COTS) acquisition, Europe's Automated Transfer Vehicle (ATV), Japan's HII Transport Vehicle (HTV), and Orion, the U.S. Crew Exploration Vehicle (CEV). These next-generation transportation vehicles demonstrate the exciting prospects for future space exploration.

The evolution of vehicles to transport crew and cargo to the ISS is representative of the evolution of the ISS. Since its original concept and design, partners and elements have been added, and elements have been



Figure 1: The ISS at assembly complete.

deleted. The changing nature of the ISS Program to date should not be seen as a failure, but rather a testament to the enduring goals under which it was created. This evolution is likely to continue over the life of the program. With new knowledge and experience, the great benefit to the ISS Program organization is its ability to adapt and continue to progress.

The ISS Program is accomplishing its near-term goals and working toward the long-term, learning how to operate in space and train the next generation of engineers, scientists and explorers. The ISS is the largest cooperative venture in space. It provides a “hands-on” laboratory for long-duration human exploration and basic scientific research. It also provides a testbed for engineering concepts that will enable future space endeavors. Similar to the lessons of the Apollo program that have been applied to the Space Shuttle and Space Station programs today, the ISS Program has much to teach tomorrow’s explorers.

NASA will utilize the Shuttle prior to its retirement in 2010 to complete assembly of the ISS. Completion and utilization of the ISS is the next critical step in exploration, the foundation to extend humanity’s reach beyond low earth orbit. This ISS foundation will offer valuable lessons, including resourcefulness, flexibility and designing with dissimilar redundancy coupled with simplicity of sparing. These lessons for future exploration will be the legacy of the ISS.

Strength of the ISS Partnership

The tragic loss of the Space Shuttle Columbia in 2003 stressed the ISS partnership and forced it to make certain accommodations. The partnership was forced to learn how to operate without the Shuttle. While temporary, it was an important lesson for the partnership prior to Shuttle retirement and yet occurred early enough to influence the early exploration work. For the ISS Program, this has led to

better mission preparation and execution techniques in areas such as logistics and resupply, on-orbit maintenance and flight operations, which have direct applicability to exploration. The prime lesson for future programs is to build resourcefulness and flexibility into their systems. Learning how to operate systems with limited resupply capability will be mandatory as exploration moves beyond low earth orbit.

During the Shuttle downtime, the partners put their proprietary interests aside, demonstrating incredible patience, as NASA brought the Shuttle back online. During this period, a number of valuable lessons were learned that changed the way the ISS Program operates. Even though assembly was on hold, there were ongoing logistics, maintenance and utilization tasks that had to be safely executed. Again the ISS partnership was learning the advantages and disadvantages of the ISS partnership agreements. This knowledge will be invaluable as international partnerships are put in place for future exploration activities.

During this period, the Russian Soyuz and Progress vehicles transported crew and delivered cargo to the ISS. This vital supply line allowed continued crewed operations of the ISS; although, the crew was reduced from three crewmembers to two from May 2003 until July 2006. With only the limited upmass of the Soyuz and Progress and the very small amount of downmass available on the Soyuz, the ISS Program planners were able to maintain the necessary resources on orbit to sustain the ISS crews and the Station: food, water, oxygen, propellant, repair tools and other supplies, as well as utilization materials. This forced planning with limited up- and downmass, taught ISS planners to reassess what must be flown to the ISS and what “work-arounds” there are, given what is already on board. Without the redundancy offered by the dissimilar transportation vehicles, support to the ISS would have been lost as a result of the Columbia tragedy.

While the crew was reduced to two, Extravehicular Activities (EVA) were performed for the first time without a crewmember inside the ISS. This meant that mission control teams on the ground had to act as the third crewmember to help monitor and manage the EVA. The U.S. and Russia had used ground controllers to monitor spacecraft systems in previous programs (i.e. Apollo, Mir), and Russia had left its spacecraft unattended during EVAs. However, the ISS Program had never intended to perform an EVA without a crewmember inside the vehicle. Therefore mission planners had the ISS crew prepare the Station to be left uncrewed, should the EVA crew not be able to return to the ISS and the ground had to control the ISS.

Also during the Shuttle downtime, the ISS crew had to repair malfunctioning flight hardware that was not originally designed for on-orbit repair. One example is the treadmill. Instead of flying a new treadmill and returning the old one to the ground for repair, as was originally conceived, the crewmembers essentially dismantled the treadmill, replaced the bearings and reassembled it in order to maintain their critical exercise regime. Russian vehicles flew smaller repair parts and tools. Ounces of upmass were needed instead of the traditional method of changing out a 75 kilogram unit. This is also a testament to the resourcefulness of the crews and mission support teams as they worked to find creative solutions when issues arose.

With limited resupply, consumables tracking took on increased importance, and systems evolved to track the consumables more accurately. This allowed the ISS Program to use the limited upmass for only those consumables that were necessary to sustain the ISS until the next resupply flight (with margin for slippage of that next launch). Better systems for consumables tracking and a better understanding of resource consumption will be a real asset for long exploration journeys.

The ISS is an integration challenge with multiple partners juggling logistics, assembly tasks and flights of different vehicles from different locations while maintaining steady-state operations. ISS Program Managers must balance the competing priorities in order to accomplish their long-term collective goals. The upcoming assembly phases will be the most challenging yet for the ISS Program. When the crews finish assembling the ISS, it will have nearly doubled in size from what it is today through numerous EVAs and complex robotic operations. This intricate assembly and operations work will necessitate the partnership work closely as a team, capitalizing on the strengths of the partnership's engineering, logistics and science communities. The ISS Program Managers, in order to "plan for the worst, while hoping for the best," will have to plan for backups and alternate courses of action at every turn. It is because of this great daring and commitment that the ISS Program will be a stepping stone that prepares the next generation for the rigors of exploration.

As the flight rationale processes and basic engineering philosophy of the Shuttle and Station today are rooted in Apollo, so too will today's lessons carry over to the next generation of vehicles. From Apollo, the Shuttle and Station programs learned how to avoid infant mortality of hardware and adopted acceptance and quality testing. ISS hardware components have to operate for multiple years, the kind of lifetimes that would be necessary to explore the Moon and Mars. Given the limits on resupply at those destinations, maintainability and reliability of systems will be essential. The ISS has redundant systems, U.S. and Russian, for all key life support functions, another benefit of the ISS partnership. This redundancy of critical systems has proved essential to sustaining the ISS. Engineers need to train with real hardware, to learn from the successes and failures and to learn how to do the next steps in exploration. The ISS Program will train those same engineers to

carry on the Shuttle and Station legacy. It was the lessons from prior space programs, such as Apollo, that enabled long-duration life on the ISS and will provide a strong foundation for future exploration programs.

“Operations centered on the International Space Station could open space to humans in much the same way that modest government investment on the American frontier forged links between curiosity and commerce, knowledge and a bright future.”² The ISS Program is also developing world leadership in space, pushing exploration in new regimes where no single country can explore the reaches of space alone. A Moon base could be constructed using the ISS model, building on its successes and learning from its difficulties. The strengths of the ISS partnership enabled the resourcefulness of mission planners and operators in order to sustain the ISS Program during this critical period.

ISS Evolution

In January 2006, the ISS partnership gathered to review the status to the program to reach an agreement on the configuration, assembly sequence and transportation plan. All three of these had been agreed to previously, but as a result of changed circumstances, the partnership had to allow these plans to adapt. The ISS Program has been forced to evolve over the life of the program, continuing to thrive because the partners have been willing to work together and compromise for the collective good and long-term success of the mission. Over time as the ISS Program continues with assembly and utilization, the definition of ISS “complete” may also continue to evolve. The ISS Program may be forced to adapt and change yet again, as the Station grows and the knowledge base increases. This is only a failure if we refuse to learn what the ISS Program can teach us.

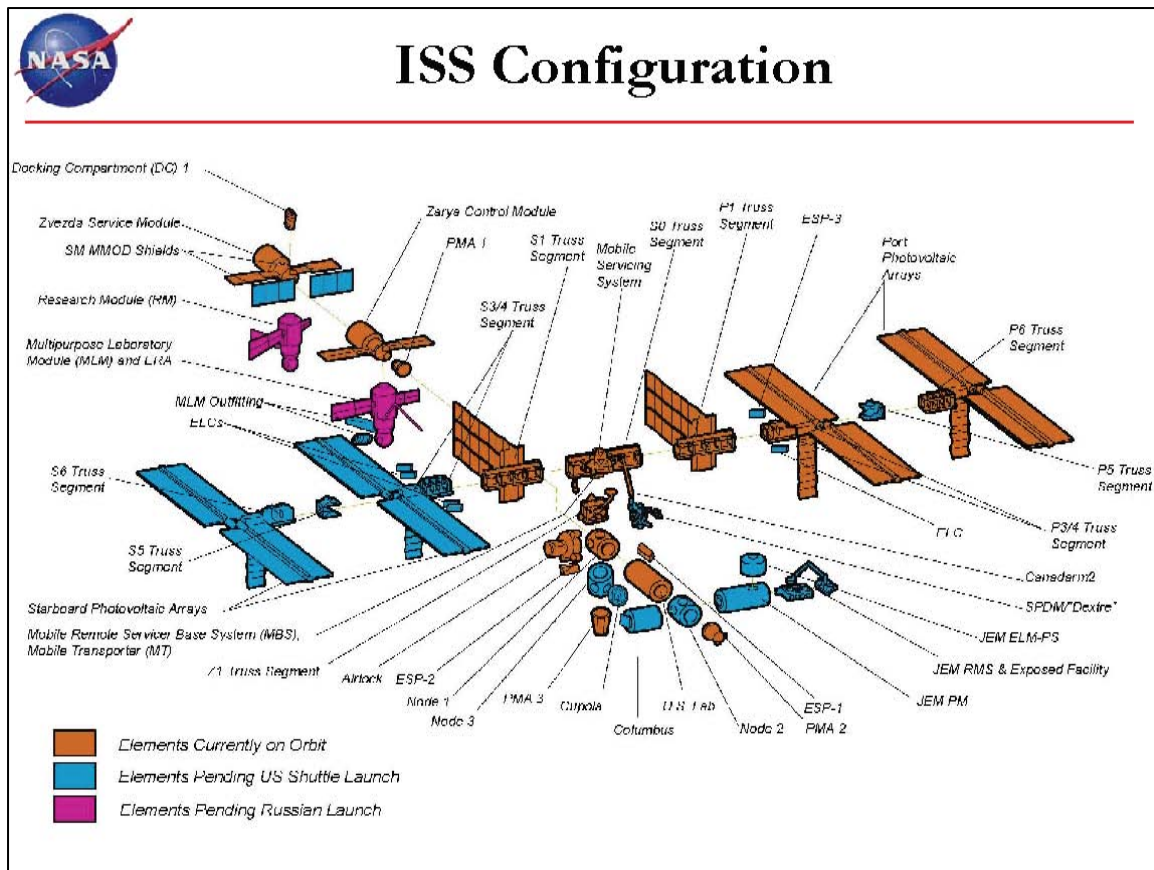
² Roger D. Lanius. “Making the Most of the International Space Station.” SPACE TIMES. (March/April 2006): 8-10.

As Station assembly continues, the partners are each demonstrating their technical prestige with elements important to their respective programs. Canadian robotics and Japanese and European laboratories will continue to illustrate the strengths of the partners’ respective programs.

As part of its evolution, the ISS partnership has been forced to modify its ongoing operations during the recent Shuttle downtime. For example, to monitor the cabin atmosphere, the U.S. and Russia shared returned air samples for analysis and monitoring. This new air sampling technique involved the efficiency and simplicity of the Russian packaging and combined it with technologically advanced U.S. absorbent material. This resulted in better and more efficient air sampling. The two agencies have also worked to combine power resources. The ISS Program does not have the luxury of excess and therefore must be flexible to maximize the available resources. From what could have been a “failure” have come powerful lessons. In the future, as the ISS partners strive to complete assembly and fully utilize the Station, there will certainly be opportunities for more such lessons.

As the ISS evolves, so too does the partnership. Similar to other international undertakings, the partners must make compromises and trades to achieve the maximum end result. The U.S., as the lead technical partner, has the responsibility for integrating the complex operations among the partnership. However, the partnership works to make major decisions in a collective, inclusive manner. The partnership has proven to be resilient, and has, to date, shown a willingness and cooperative spirit to work out any differences or balance competing priorities.

While many countries might prefer to go to the Moon or Mars on their own, technical or physical constraints and limited resources will force various nations to integrate



exploration efforts to maximize their national goals. The cooperation lessons from the ISS, along with other international cooperative research and technology ventures, might be viewed differently depending on which partner one asks; however, there is some commonality to the collective experience that can be passed on to future exploration programs. Such integration can occur because it is forced due to unforeseen circumstances or because it is planned. Arguably it is better to work as a team to plan for integration and resource sharing than to default into a survival path because of some dire situation. There likely will be more countries that move on to lunar or Martian exploration than just those involved in the ISS, but the experience of the ISS partnership will certainly have lessons for the next generation of exploration.

ISS utilization has also evolved over time. Research has been conducted on orbit since the first element of the ISS was launched. Performing scientific experiments, beyond those related to human long-duration research in which the crew on orbit *is* the experiment, was difficult while the crew was reduced to two. As more elements are joined to the ISS and the crew expands from three to six, utilization will increase significantly, bringing the ISS Program closer to the capabilities envisaged at the Station's conception.

U.S. research has been redirected to focus predominately on exploration, while the other ISS partners are carrying out essentially the science program they had originally planned. As with other research fields, some of the most interesting discoveries to date have occurred when the researchers weren't striving for a particular outcome or trying to prove a certain theorem.

One such example is the development of ultrasound techniques on the ISS. Designed to facilitate medical treatment on orbit, the application for ultrasound and telemedicine can be seen on the bench at a major league hockey game and in rural communities without high tech medical capabilities. It is this discovery, as opposed to conformational research, that excites researchers and will maximize our learning for our next steps in exploration. "...space explorers have prepared for their journeys...some have become heroes, some have met their deaths; the vast majority did their countries proud by simply performing the duties in which they had been meticulously trained – often accompanied by the unexpected events that are the hallmark of exploration."³

A new biosensor experiment onboard the ISS "could yield ultrasensitive biosensors as well as a new surface treatment that repels bacteria for surgical tools like catheters. It could also serve as a test bed for medical researchers trying to understand how some bacteria, such as tuberculosis, can survive long periods of dormancy within the human body."⁴

In one of the Binary Colloidal Alloy Tests (BCAT) "...astronauts photograph samples of polymer and colloidal particles (tiny nanoscale spheres suspended in liquid) that model liquid/gas phase changes. Results will help scientists develop fundamental physics concepts previously cloaked by the effects of gravity.... Critical phenomena are not only an area of tremendous interest from a fundamental physics perspective, but also have a number of important technological applications, ranging from the extraction of delicate complex pharmaceutical molecules

from plant materials, to understanding the behavior of oxygen as it exits a rocket engine at extremely high temperature and pressure."⁵ In addition to the experiment itself, the BCAT combined with the camera from Earth Knowledge Acquired by Middle Schools (EARTHKAM) are "cooperating in an effort to maximize (our) science return while reducing the demands on crew time to perform the experiment and transmit the data to Earth." The EARTHKAM hardware was used to automatically photograph the BCAT, alleviating some of the crew time requirements and providing the images to researchers on the ground sooner.

One of the key lessons for exploration from the ISS Program is the value of building flexibility into the system. The evolution of the ISS has demonstrated this essential component of future exploration by adapting to changed circumstances to achieve the ultimate goal. Whether it was using old tools for a new task or having multiple supply vehicles, the ISS has illustrated the value of flexibility in systems, processes and people.

On orbit Test bed for Exploration

The ISS Program is an on orbit operations, technology development and international cooperation test bed for exploration. Just as the ISS Program is building on the lessons from early American and Russian space programs, so too will the next exploration endeavors to the Moon and Mars.

ISS operations have evolved from previous program experiences and have continued to evolve over the life of the Station. A prime example is the ground support infrastructure that supports ISS flight operations. During Shuttle operations, especially prior to the ISS, the Mission Control Center (MCC) supported the Shuttle with nearly full

³ Steven J. Dick. "Why We Explore: The Voyagers." (June 29, 2006). http://www.nasa.gov/mission_pages/exploration/whyweexplore/Why_We_21.html (accessed July 26, 2006)

⁴ Colin R. Johnson. "Biosensor made of living cells takes off for space." Electronic Engineering Times. July 31, 2006.

⁵ Julie Robinson. "BCAT-3-CP". ISS Program Scientist Toolbox. <http://exploration.nasa.gov/programs/station/BCAT-3-CP.html> (accessed August 15, 2006).

subsystem teams around-the-clock. This is feasible when the Shuttle is only in flight for approximately two weeks at a time. With the continual around-the-clock operations of the ISS, that type of full-up, around-the-clock support was costly and draining on personnel. Now there are significantly less personnel in the MCC while the crew is asleep or less active.

With the advent of the ISS Program, control centers across the globe are coordinating daily operations. The prime control centers in Houston and Moscow jointly work with the ISS crews every day. As more partner elements are joined to the ISS, control centers in Europe, Japan and Canada will also become active, requiring close coordination and integration on the ground as well as on orbit.

Scheduling crew days has also changed over time. Instead of scheduling crews on minute-by-minute timelines (Apollo and Shuttle) for Station operations, there is more flexibility built into the crew timeline. There is scheduled free time and a “job jar” for crewmembers to work on as they have time. This enables the crew to have some choice among tasks and timelines. This increased crew autonomy will be instrumental as spacecraft travel further from Earth, delaying MCC communications with the crew. The ISS Program has also been able to minimize ground support for certain repetitive tasks with support available for the crew as if they were in their office on Earth.

The ISS is a test bed for continuing operations improvements to prepare for extended missions beyond earth orbit. The ISS Program has worked to increase communications capabilities and minimize ground support for some of the routine tasks. “Operations protocols and support tools which minimize the ground support infrastructure needed to monitor and control spacecraft systems are also essential for long duration missions. The ISS operations concepts and ground facilities continue to

evolve due to ongoing efforts to increase effectiveness and minimize operations costs.”⁶

Another example of both technical and international advances in operations is joint EVAs from the ISS. An ISS crew has now performed an EVA with crewmembers in Russian suits working on the U.S. segment, during which both MCCs, in Houston and Moscow, supported the crew using the Canadian-built arm to monitor the crew’s progress.

Robotics are an essential partner in efficient on orbit operations. By the time the ISS is fully assembled, the Canadian robotic arm will be joined by Japanese and European arms to work on different portions of the ISS. These robotics can be commanded via the ground or by the crew on the ISS. It is this multi-system approach that has been elemental to the successful operation of the ISS to date and will become even more critical over the lifetime of the Program.

Ground teams are performing solar array pointing by using timed/bundled/scripted commands. This saves the ground teams from sending hundreds of ground commands to point the solar arrays. Learning to use this script language when distances are too great for ground commanding will be invaluable for operations on Mars. Again the ISS is serving as a test bed for activities that will be mandatory for exploration.

The technology development of the ISS can also provide lessons for exploration. The experience of assembling components in space for the ISS is applicable to assembling components on the Moon. The avionics software has been updated on nearly the entire spacecraft, increasing efficiency. Life support systems are still being developed for future launches to the ISS. Closed loop life

⁶ Gary Kitmacher and Theresa Maxwell. “Furthering Exploration – International Space Station Experience.” SpaceOps2006 Symposium (June 2006): 6.

support is being demonstrated on ISS. This will drastically reduce the amount of consumables needed to be carried in future exploration missions. Having both U.S. and Russian life support systems provides a dissimilarly redundant capability that is applicable to future exploration missions.

Dissimilar redundancy, paired with simplicity of sparing, provides a hedge against generic system failures and minimizes the amount of spares required to be stored on orbit. Simplicity of sparing simply uses the same components in multiple systems. For example, a common valve design fits in multiple systems or one motor drive actuator in multiple different systems. The problem with this sparing concept is that it is susceptible to a generic failure which takes out multiple systems. For this to be effective, the reliability of the common components must be high. In order to balance these two concepts, performance data from the ISS can be applied to future systems. The ISS allows us to experiment and learn before these concepts critical to exploration become mandatory to successful operations.

Multiple supply vehicles to the ISS will provide the essential logistical flexibility that will prove invaluable to the ISS Program. The U.S. Space Shuttle, Russian Progress and Soyuz vehicles currently in operation will soon be joined by the U.S. Commercial Orbital Transportation System and Crew Exploration Vehicle, the European Automated Transfer Vehicle and the Japanese HII Transfer Vehicle. The criticality of multiple transportation systems became all the more clear while the only vehicle capable of launching the large ISS elements, the U.S. Space Shuttle, was grounded, delaying ISS assembly. This multi-vehicle approach illustrates that while international cooperation can be an integration challenge, there is the potential for great reward.

The technology development of the ISS Program is a testbed for future exploration

programs. Mission operations, technological advances, multiple transportation vehicles and support systems are prime illustrations of the value of the ISS Program in building a base for the next exploration programs. Designing systems with dissimilar redundancy paired with simplicity of sparing will help to buy down risk for the explorers of the future.

Summary

Future exploration programs would do well to remember that if the current ISS program was measured in light of its original design, we might consider the ISS a failure. That would clearly be wrong. Because of its ability to evolve and adapt, the ISS Program is demonstrating its success through daily operations and utilization and will continue to be successful through assembly and beyond. The ISS Program has pushed space exploration in new and different ways and will allow us to try new and better strategies in the future.

The strength of the ISS partnership in light of unforeseen challenges illustrates the need for programmatic resourcefulness. The evolution of the ISS over the life of the program has shown that flexibility is critical to mission success. Designing and testing ISS systems with dissimilar redundancy and simplicity of sparing demonstrate that the investment in the ISS as a testbed for exploration is continuing to provide lessons for the future.

Just as Magellan and Columbus set out to explore the far reaches of their world, using the knowledge gained from the sailors that had gone before, so too will future spacefarers that explore the Moon, Mars and beyond, using the knowledge and experience gained from the ISS Program. It is the duty of the ISS partnership today to fully utilize the ISS in order to provide a strong foundation for future explorers. It will be the duty of those explorers to make the most of the ISS lessons.

“Wilbur Wright expressed this philosophy very well when he compared flying to riding a ‘fractious horse.’ Speaking in Chicago before the Western Society of Engineers in September 1901, he said: ‘Now, there are two ways of learning how to ride a fractious horse: one is to get on him and learn by actual practice [and] the other is to sit on a fence and watch the beast.... It is very much the same in learning to ride a flying machine; if you are looking for perfect safety, you will do well to sit on a fence and watch the birds; but if you really wish to learn, you must mount a machine and become acquainted with its tricks by actual trial.’ In short, the Wrights exemplified the airman’s philosophy, the belief of the practitioner that actual experience must accompany theory.”⁷ The ISS Program is providing the actual experience for exploration theory.

The next generation of scientists and engineers, the next explorers, have a responsibility to learn the lessons of previous programs, such as the ISS, in order to have an optimal chance of success. Designing systems with resourcefulness, flexibility and redundancy is just a small sample of the lessons the ISS will offer to the next generation of explorers. The entirety of the lessons from the ISS Program will only become clear in the eyes of future generations.

⁷ Richard P. Hallion. “The Wright Brothers-How They Flew”. *American Heritage Invention and Technology Magazine*. Fall 2003. Volume 19, Issue 2.
http://www.americanheritage.com/articles/magazine/it/2003/2/2003_2_18.shtml (accessed August 14, 2006).

